APPLICATIONS OF ELECTRONICALLY SCANNED ACOUSTIC IMAGING TECHNIQUES TO NDE*

Gordon S. Kino
Stanford University
Stanford, California

I am very grateful to Bob (Dr. R. Addison, the previous paper) for giving you a fairly detailed definition of all the possible systems. It makes my life a lot simpler. You have helped me a lot in saying all kinds of things our system cannot do. I say, "Oh yes, but we can do some of these things. They are true." So, let me try.

Bob already talked about C-scan systems and I'd like to refresh your memory a little here. In particular, I want to talk about a C-scan system which has been used by Caustin on the B-1 project, in which we had considerable interest because we have been taking some of his samples and measuring them, he having measured them earlier.

Now, why do we want to use our electronic scanning system as opposed to the typical system that is, say, being used by Caustin and other people? His system basically consists of a transmitting and a receiving transducer focused to the same point. The object is moved mechanically along in the x direction, and the transmitting and receiving transducers are moved back and forth in the y direction, as shown in Fig. 1. Thus, a raster is scanned out. The system works, and it works well, and the electronic focusing systems aren't going to do any better; this is really because electronic focusing systems are just lenses. They have the same kinds of apertures, so the same laws of physics limit the definition.

The advantages of electronic focusing systems are more flexibility and speed. What we would like to do is obtain something of the order of a millimeter definition. So, if one could only speed up the scan in one direction, and use, say, a line time of the order of 60 μsec across 3 inches or so, that would change the time for scanning the same object from hours to minutes. It is, of course, possible to go all the way to real time and obtain real time images. Increasing the speed in one direction is obviously important.

Now, there are other things you might want to do. If you want to look at thicker objects, you would like to be able to automatically focus in and out. You might like to be able to focus in and out in the z direction and scan back and forth in the x direction. Again, if you can carry out this process electronically at high speed, this would be very useful. Of course, the ultimate aim is to obtain good definition in all three directions: the range z, and the transverse directions, x and y. This is what we have been working towards, and I want to describe a series of array devices on which we

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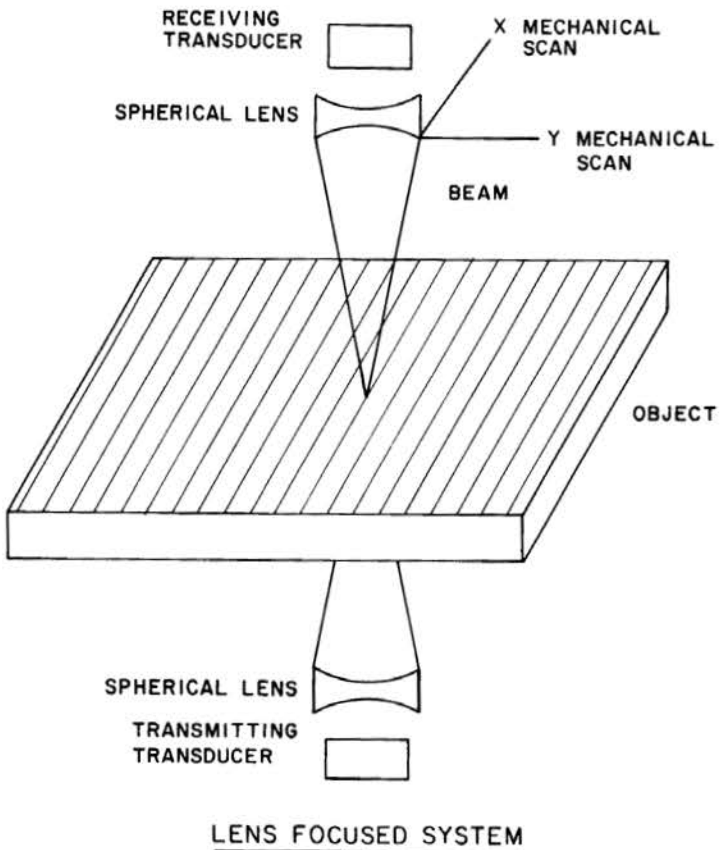


Fig. 1. Schematic diagram of apparatus with 2-dimensional mechanical scanning.

have been working, which essentially demonstrate the various principles required. I also want to describe various kinds of NDE samples that we have looked at with these devices, and with which we basically demonstrated their feasibility.

I am going to first describe an 83 element C-scan receiver system briefly alluded to by Bob, which, incidentally, uses all 83 elements at a time, not just 20 at a time. This is the work of Shaw, Winslow, Leung, and Fraser. I am also going to describe very briefly a C-scan system, which is the work of Kino, Waugh, and Havlice, that scans electronically in both directions. It is a sparse system, i.e., it has 2N elements for N^2 resolvable spots, and has a frame time of the order of 30 Hz. I am then going to describe a focused B-scan system which uses the same array for both transmission and reception and gives good range and transverse definition at the same time. This is the work of Kino, DeSilets, Fraser, and Waugh.

Suppose, now, that we could take the Caustin system that I have already discussed and we could use a transmitting array in the y direction, as shown in Fig. 2. We could then scan fast in the y direction, and, if we used the focused transmitter to focus on a line in the x direction, we could speed up the scan. We would then only be limited by the mechanical scan rate in the x direction.

Now, just to describe the basic principles of our present system, let us talk about a one dimensional receiving system. First of all, we consider an array of piezoelectric transducers, imaging an object that is illuminated by a sound wave of frequency ω_S. We use a surface wave delay line which has a series of taps on it, one tap to a transducer. We take a signal out from a tap and a signal out from the corresponding piezoelectric element, we mix them, and sum the outputs of the mixers. We could use diode mixers, but the real system is more elaborate; we use more elaborate integrated circuit mixers with more efficiency, with amplifiers on each element, and so on. We obtain a product signal from a tap and the corresponding transducer, which is at the sum frequency, or at the difference frequency, as the case may be. That product signal contains information not only on the amplitude, but it also contains information on the phase of the signal arriving at the transducer. This is important for focusing.

Now, if we send in a pulsed rf signal along the delay line, there will only be a signal present at a particular element when the pulse passes by it. So, we will sample the signal from the corresponding element, and the output will come out of the sum line. This is the most elementary system.

If you will now imagine that there is a line source at a point (x,z), as shown in Fig. 3, and look at the signal arriving from the line source at the array, the different rays from the source follow different paths to the paraxial approximation; the difference in lengths of the rays are essentially proportional to the square of the distance from the point x on the array. If we can put a parabolic variation of phase along the delay

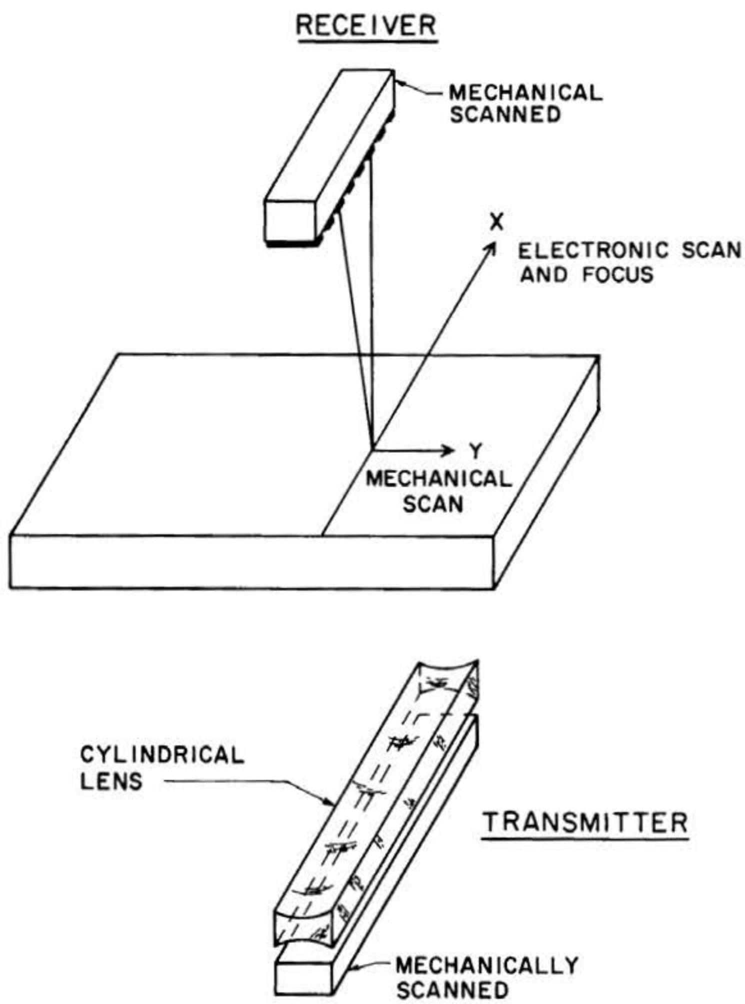


Fig. 2. Schematic diagram of apparatus with combined electronic and mechanical scanning.

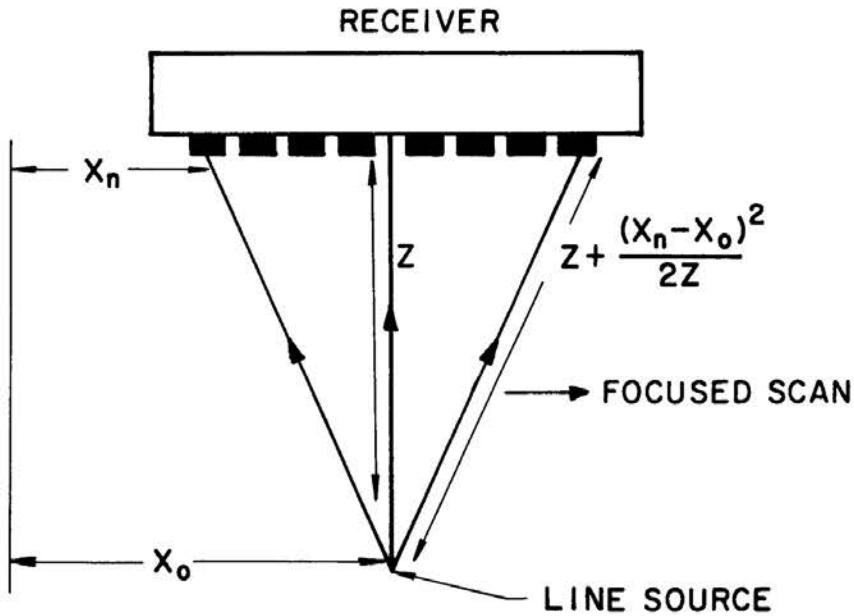


Fig. 3. Diagram of receiver geometry.

line, we can add up the signals from all the elements of the transducer. What this really means is that we have used signal processing techniques to make a matched filter, matched to the line source.

How would we obtain that square law variation of phase? If I insert a so-called linear FM chirp into the delay line, a linear variation of frequency gives a square law variation of phase, and that, in turn, is translated to a square law variation of phase spatially along the delay line. What that means is that we put a simple linear FM chirp into the delay line, as it moves along it, it focuses on a distant point, because the phase matches the phases from the distant point. It moves along and scans that point, then the next point, and the next point, until it automatically scans one line parallel to the array. We can sum this up mathematically. We insert a chirp signal with a frequency variation $\omega = \omega_1 + \mu t$, linear variation in frequency. It focuses on a line source at (x_0, z), where z is the distance from the array. The image is obtained at a particular time $t = x_0/v$, because the chirp moves along the array with a velocity, v. At a particular time, we look at a particular point, (x_0, z). It automatically scans.

By varying the chirp rate, we can vary the parabolic variations of phase; that means we can vary the focal length of the lens electronically by varying the chirp rate. We can show that the relation between chirp rate and focal length is $z = 2\pi v^2/\mu\lambda$, where λ is the wavelength of sound.

Before discussing some of our imaging devices, I want to illustrate one more point and to tell you what some of the implications are in terms of the flexibility of the system. After listening yesterday to various speakers, it seemed to me that I ought really to emphasize this feature of electronically focused systems. We consider a point source and suppose that the point source produces an output signal, which is a function of angle. This is, of course, related to what was discussed in prior papers, that we can use such a result to obtain information on the nature of the source. What I have already said is that, if I had an array system, I could focus on any part of an object. If the object were much bigger than the wavelength, I would expect to get an image that I could recognize. But, if the object were too small, below the Rayleigh size limits, then imaging is not possible. Then, as was indicated in several prior papers, the angular scattering information will still give us some information about that flaw. An array system can be used both for imaging and to obtain scattering data. If, for example, we just send a pulse along the delay line, the array has a certain amplitude distribution along it, proportional essentially to the angular response from a point source, i.e., the output from any element is just going to be proportional to θ times the response of the array. So, we can obtain a direct measure of the angular response from some point. Alternatively, if we focus the system on the point and use the array, what you find out, after a little mathematics, is that the output is essentially the Fourier transform of this angular response. We can then, using the delay line system with acoustic signal processing, very easily find the inverse transform and get back the original response, if we want to. That has certain advantages, because it means we can easily focus on a particular point and make sure we're looking at that point and not at another point. So, it may be convenient to do it that way.

Now, let us go back and discuss how this system is used to look at NDE samples. In particular, what we have been looking at are samples of boron fiber reinforced epoxy laminates laid down on a titanium backing which were supplied to us by the people on the B-1 project. These are samples that they have already looked at; specially made samples with all kinds of flaws in them. Our aim has been to find the flaws and see how well we can define them. The system we have used for this purpose is an 83 element receiver system, which is, admittedly, in a fairly crude state. It was built about a year ago. We have not modified it since then. We know there are all kinds of faults in it, but these systems are expensive and we just have not wanted to tear it down and start again, although we now feel we have experience and could clean it up immensely. What I am really saying is it still has a fairly high side lobe level.

We combine the electronic scanning with mechanical scanning, and put the object in the water tank with a strip transducer behind it; we mechanically scan the object up and down, as shown in Fig. 4. The samples we are using are about 3 inches wide. We scan the width of the sample in 60 μsec, and we are limited in the scan time in the vertical direction by, essentially, the rate at which we can scan mechanically. In the most recent system, we scan 9 inches in the vertical direction.

Figure 5 shows a picture of a sample with debonded regions that have been deliberately introduced into it. It can be seen that the system picks out the holes very well. There are a few, I think, minor artifacts, but you can see that we do, indeed, pick out the various holes. Now, this is a thin sample about 3/16 of an inch thick, and the system does quite well in recognizing the various holes and flaws in the sample. And, as I have said, this is done essentially in one mechanical pass. This is a tremendous increase in speed over that of a purely mechanical scan. The definition is actually of the order of 1-1/2 mm at a distance of about 15 cm.

Figure 6 shows a thicker sample 1/2 inch thick, that we have looked at. Remember, now, this is really difficult material to measure, because of its high attenuation. As you might expect, our pictures are not so perfect. I think you can see we are picking out the major flaws, but we are not doing so well with the minor ones. Again, there are a few artifacts. At the moment we are just using a strip transducer behind the sample, and, of course, what we eventually intend to do is use a cylindrically focused beam. We had a little trouble with our lenses, so we are not really ready to do that yet. But we are building lenses for that purpose, and then I think we will do much better on the thicker samples. We also need a very high transmitter power, because the samples are very, very lossy.

I now want to discuss very briefly something we talked about at the last Ultrasonics Symposium, a two-dimensional electronic scan. We can scan

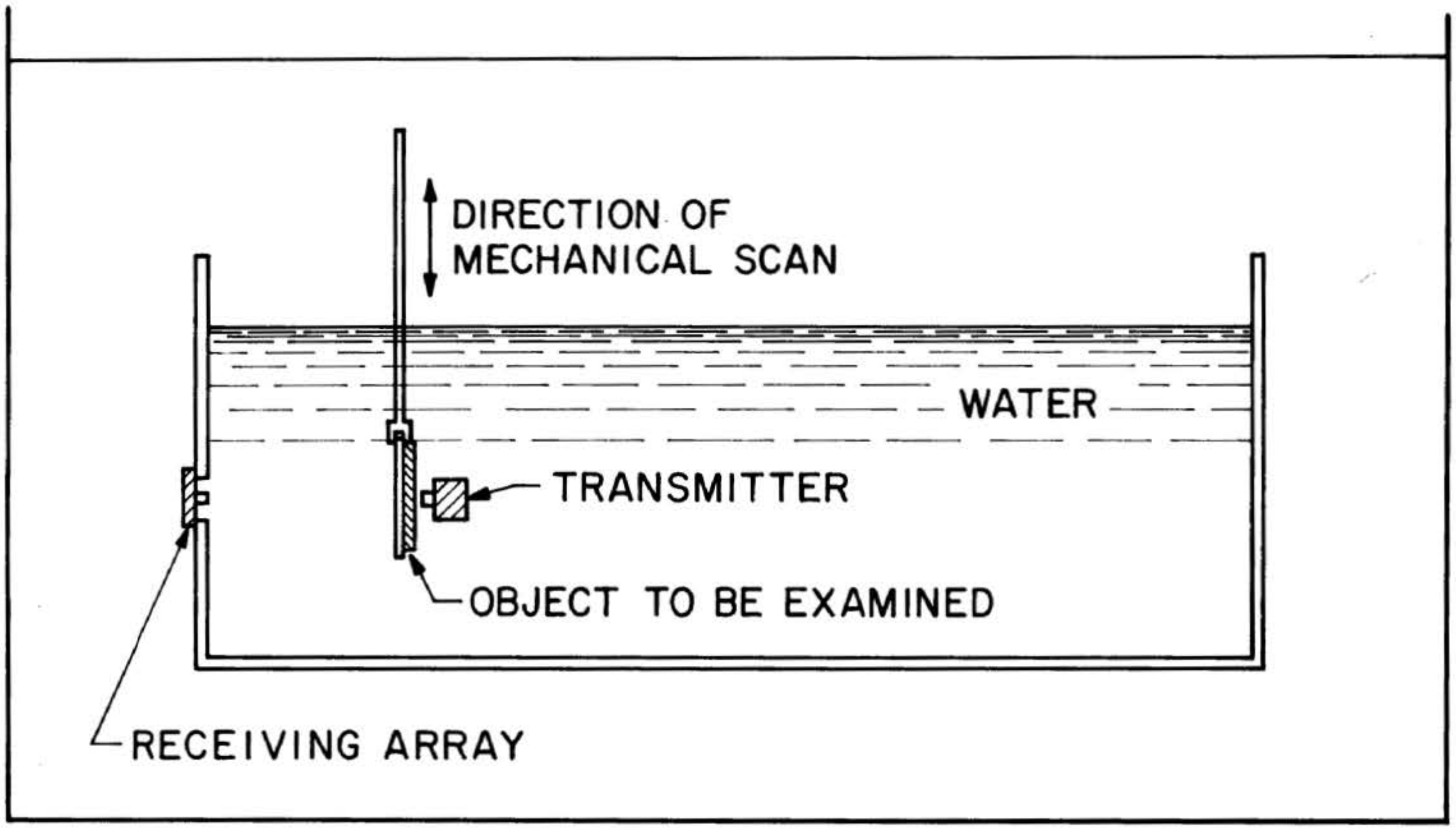


Fig. 4. Schematic diagram of apparatus in water tank.

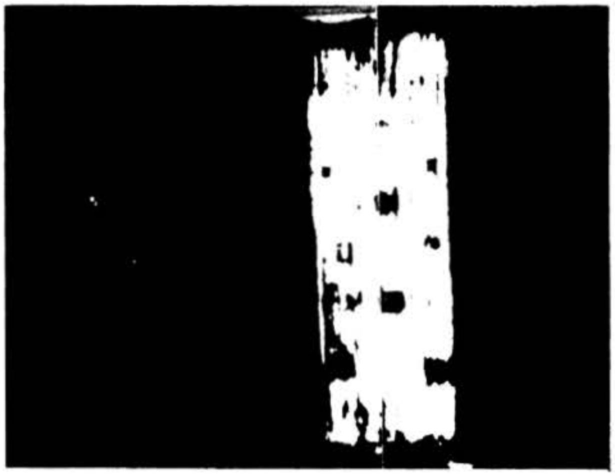


Fig. 5. Image of 3/16" thick sample with debonded regions.

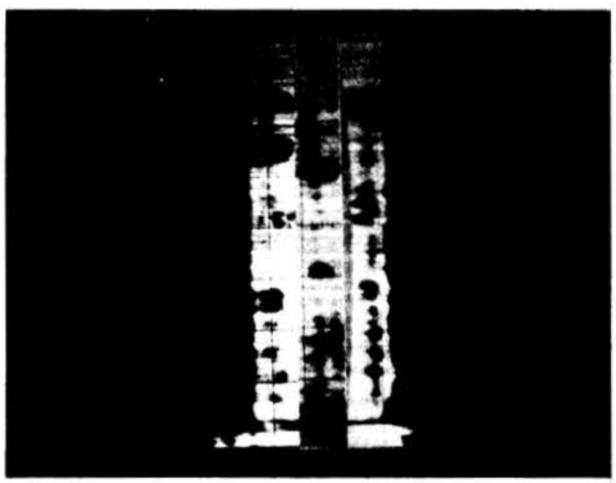


Fig. 6. Image of 1/2" thick sample with flaws.

with a sparse array by using one array as a transmitter, as shown in Fig. 7. By reversing the receiver process I have already described, we can make a transmitter to produce a focused beam, putting signals into the transducers, instead of taking them out of them, with the appropriate chirps sent along the delay line. We can actually scan at any rate we wish, the scan does not have to be determined by the acoustic velocity on the delay line. We can obtain a fixed focus, for instance.

In this way, we obtain a slowly scanned line focus. We then use a receiver array, placed at right angles to the transmitter array, to obtain a line focus in the x direction. So, as the receiver scans across the x direction, if the line focus of the transmitter were stationary, for instance, we would scan along one line. Then we would move the transmitter line up in the y direction and go to the next line, and thus eventually scan out a raster. The system is very crude, it has 22 elements in the receiver and about the same number in the transmitter. That means that, ideally, you can obtain 22 times 22, or 484 resolvable spots with only 44 elements. You lose in power, and so on, and have various other problems, some of which were associated, essentially, with the poor electronics. This contributes mainly to high side lobe levels, which is the plague of electronically focused systems.

Figure 8 shows a crude picture we took in real time with this system at a 30 Hz frame rate. It is a picture of just a simple letter cut in a piece of rubber. In the picture you can see examples of defocusing the horizontal focus by about 25%, and similar defocusing in the vertical direction. The focusing is obviously there.

I worry about side lobes all the time, because they limit the dynamic range. If there is a side lobe about 15 dB down from the main lobe, this means your dynamic range, at best, is limited to about 15 dB, because some point away from the focal point will also give you a 15 dB signal, just 15 dB down from the main lobe. There are worse possibilities. If you are looking at, say, a long continuous source, the side lobes tend to add up and so you get very large ripples or dark bands in the output. One way of eliminating some of these problems is to use an incoherent source. We tried that, using a noise input with a 500 KHz bandwidth. It helps, but tends to ruin the definition.

If, instead, as was suggested by Bob, we use a focused transmitter and receiver, we only illuminate the point of interest and don't look at the side lobes. Then you should do much better, because not only do you get rid of the side lobes, and, hence, have no ripple from a continuous source, but you also have the great advantage of getting better definition because of the focusing by both lenses. The theory, in fact, indicates that you can use lenses with approximately half the aperture for the same definition. This is very important, because it means one can use a much shorter array. We have made such a system operating in a reflection mode. It is at a very early stage and has only been operating for a short time. We have various problems with the array, so it is not by any means perfect. As yet, its dynamic range is still limited due to ringing in the array, which I think is a soluble problem. We use the system first as a transmitter, using the same array for

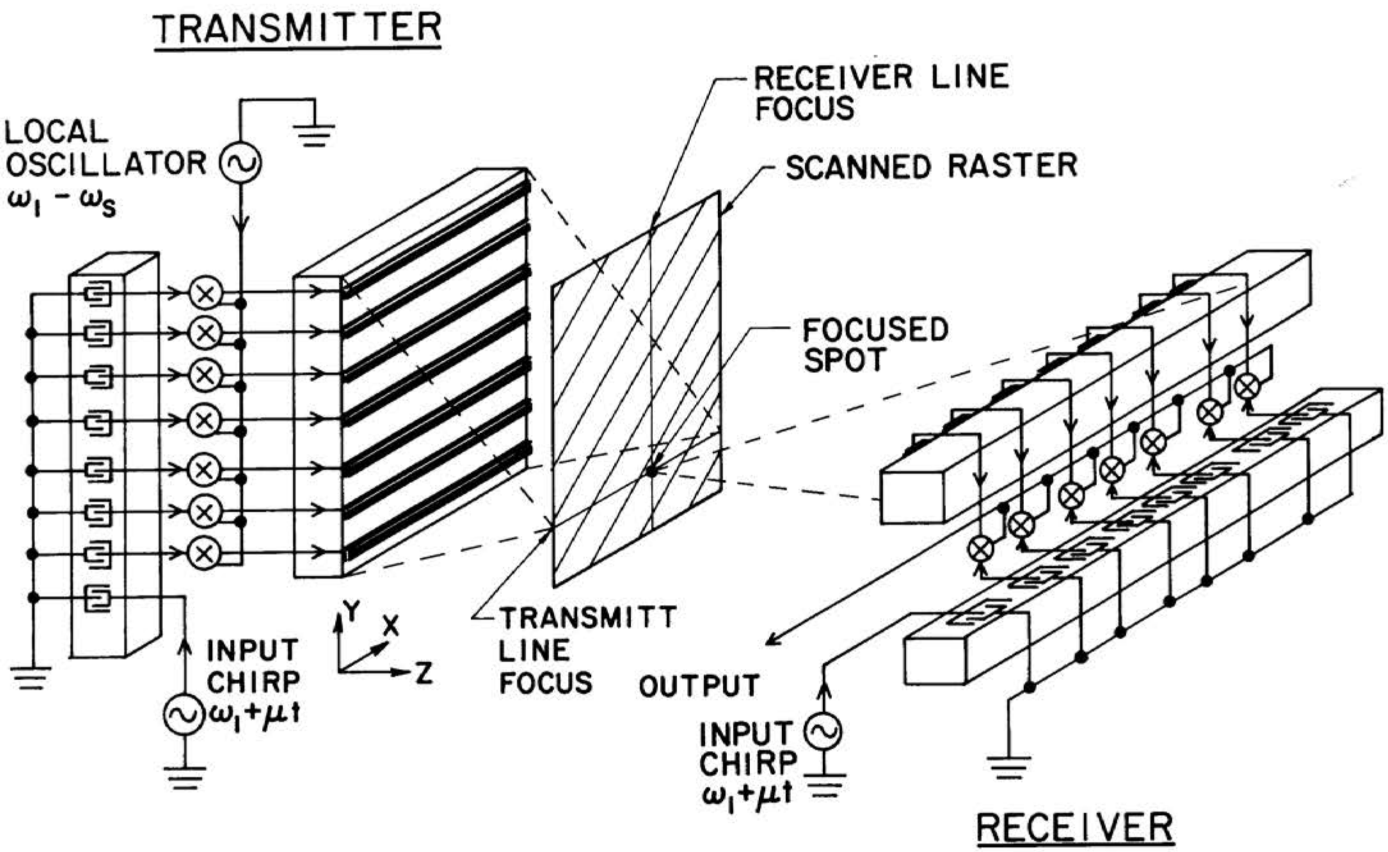


Fig. 7. Schematic diagram of a two-dimensional electronic scan system.

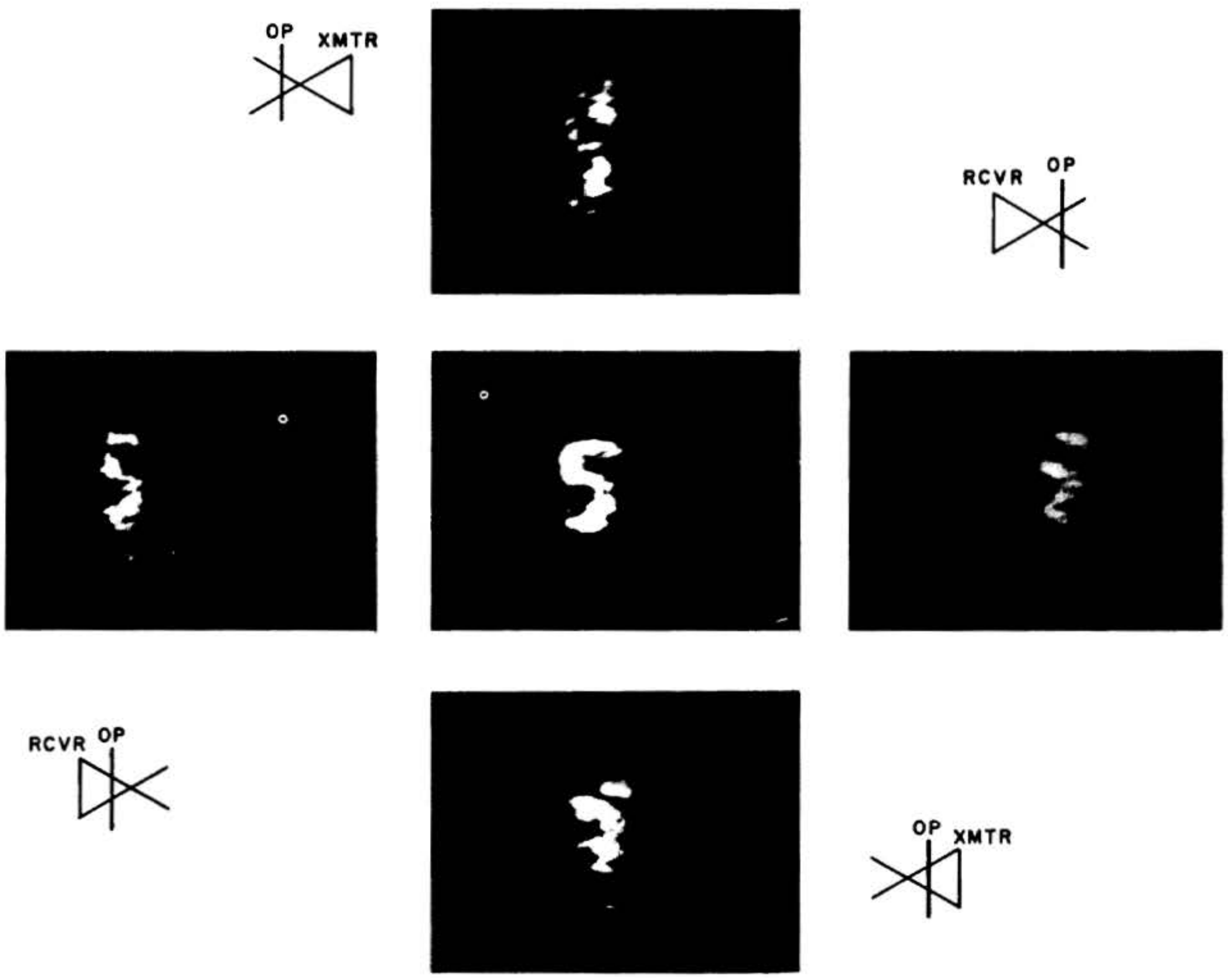


Fig. 8. Images taken with 2-dimensional electronic scan system.

transmit and receive, as illustrated in Fig. 9. It behaves like a lens which is moving along a line. So, we focus on a particular point a distance z from the array, and then scan a whole line. Then we use the device as a receiver, with the moving lens focused and scanned along the same line. We can only look at a particular point if we have the right time delay between receive and transmit. If we look at a point farther out from the array using the same time delay, the receiver lens will have moved further along in the x direction and the receiver won't see that point. Similarly, if we look at a point at a different transverse position, the receiver lens is not in the right place to pick up the signal from the point at the right time. So, we scan a line and obtain good range definition comparable to the transverse definition of the system. We scan the system in the way shown in Fig. 10, scanning along lines parallel to the array. We scan one line, then we go to the next line, changing the focus and time delay between transmit and receive. The advantage of this scheme over that in which the focus is scanned radially, as shown in Fig. 10 (the Thurston system), is that we can focus both transmitter and receiver tightly. You can only focus the receiver in a radial scan system.

The system is actually very simple. It uses a single delay line, and the signal processing is contained on a small board. No computer is required. Because of the limited dynamic range of the system at the present time, we looked at specular reflections from a simple metal sample in a water tank, a stepped metal sample with the array facing it, as shown in Fig. 11. The stepped metal sample is compared to the reflected acoustic picture in Fig. 11. You can see that, in fact, we are obtaining about 2 mm definition in each direction at a distance of 15cm, using 2.2 MHz acoustic waves. As you can see, we obtain good transverse definition, as well as good range definition. As this is a specular reflector, we are only seeing reflections from the metal faces parallel to the array. The present system has about a 20 cm field of view in the normal direction for the array, and about 6 cm in the other direction. I want to emphasize that these arrays have various kinds of capabilities and they are very flexible, but they need a great deal of engineering development, because of the precision with which you need accurate amplitude and phase at each element.

We have demonstrated a number of basic principles. We believe that, with effort, we can develop these systems to, first of all, produce very good images in real time. Secondly at a later stage, we believe that they can be used for phase contrast imaging, and for other kinds of operations which will show up more quantitative parameters like stress. They can also be used on very small flaws to give a measure of the angular scattering from a small flaw, which, again, will give us information about small flaws. We are by no means at the stage where we have demonstrated all those things, but I think we have demonstrated the feasibility of the basic system.

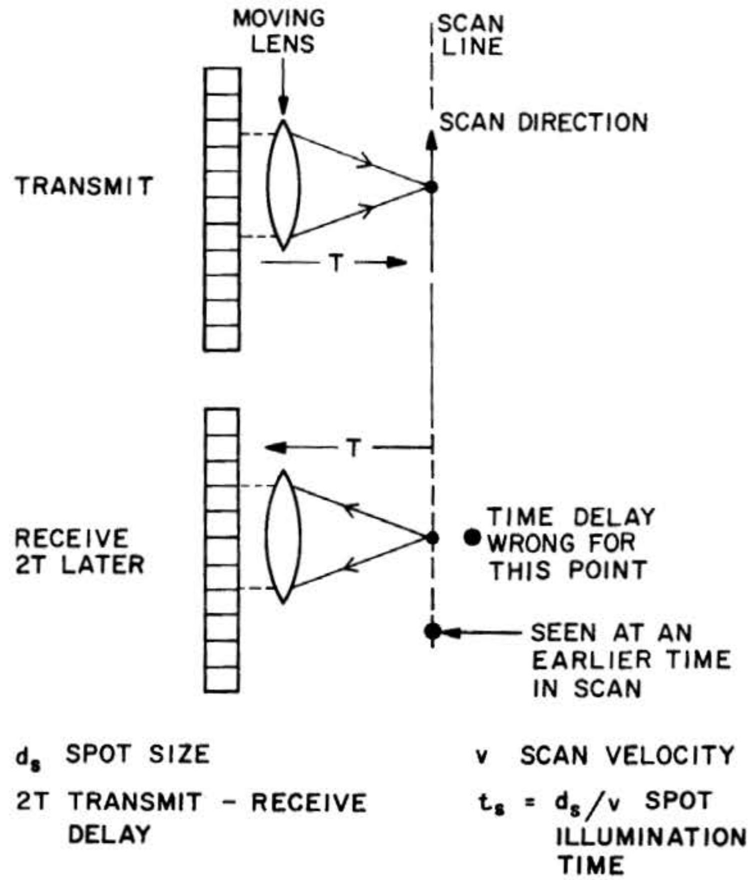
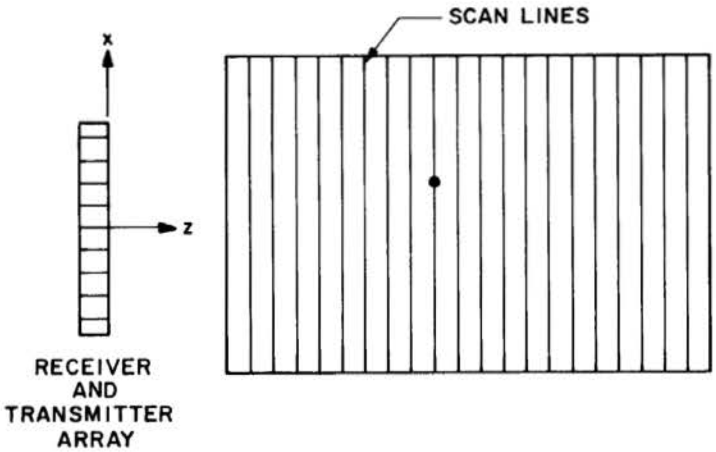
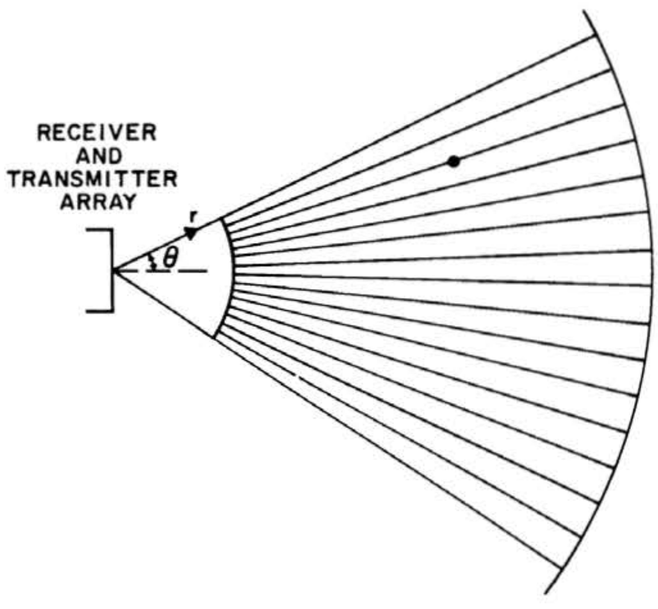


Fig. 9. Focused transmitter-receiver transducer arrangement.



(a) B SCAN - SCAN LINES PARALLEL TO ARRAY



(b) B SCAN - RADIAL SECTOR SCAN. SCAN LINES ARE RADIAL.

Fig. 10. Scan patterns of (a) the Stanford transmitter-receiver system and (b) the Thurston system.

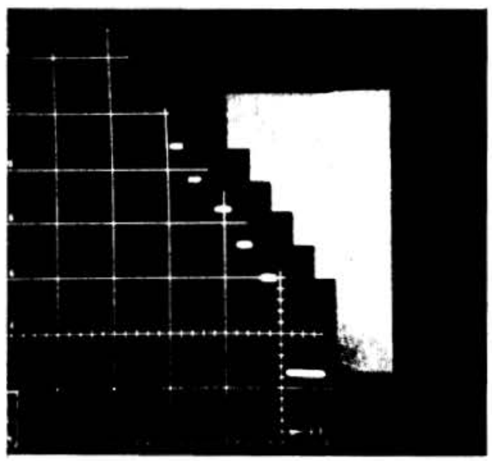


Fig. 11. Image of stepped metal sample.

DISCUSSION

DR. CRIST (Wright State University): I would like to limit the discussion to one question.

DR. JIM SEYDEL (University of Michigan): Would you comment on the sensitivity of your system for looking at the interior of aluminum, carbon, and steel samples, say, 1 to 6 inches thick?

PROF. KINO: Yes. This is a matter of transmitter power and receiver power. They are no better and no worse than any other system that way. At the moment, we are using a rather limited transmitter signal, which would be in the range of 5 to 8 V, peak to peak. We can shove that up, but we have about 60 dB in hand in the receiver. That means, if we lose 20 or 30 dB going into a metal, we have another 30 dB in hand at the present time. At the moment, the problem is dynamic range. It so happens that, after the transmitter is turned off, there is still some signal floating around in the array; thus, we can still see the transmitter signal which is limiting our dynamic range. Presuming we get rid of that, which is certainly possible, people have done this already in arrays, then we should be well off, for we have about 30 - 40 dB available. By increasing transmitter power, which we can do, then we should be in the same class as any other B-scan system.

DR. SEYDEL: What do you think is the maximum voltage that you can put on those piezoelectric elements?

PROF. KINO: About 100 V. It could be more than that, but remember now that this is a focused system, so you do have the advantage...and we have certainly noticed that, we have certainly measured it...you do have the advantage that all the elements contribute to the signal at a particular point, both in receiving and transmitting. So, it is as if you have this 1 inch diameter array with all the power going into the point of interest, and that means that we don't really have to belt this as hard as you typically do in these systems. As you can see, we are in the signal processing game!